Fatigue Design for Concrete Bridge Structures

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In a three-part series published in the Summer 2011, Fall 2011, and Winter 2012 issues of *ASPIRE*®, Dr. Dennis Mertz provided an overview of the fatigue limit states specified in the fifth edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] and explored their applicability to concrete structures. Since that series, there have been changes in load factors for fatigue and other changes in resistance and approach, which are summarized in this article.

It may seem odd that fatigue is being discussed here—isn't that only a problem for steel structures? Although more attention is paid to fatigue for steel structures, concrete structures are not exempt. A review of Section 5 of the ninth edition of the *AASHTO LRFD Bridge Design Specifications*[2] finds various fatigue requirements for concrete structures.

Specification Requirements

In Article 5.5.1.1, Limit-State Applicability, the AASHTO LRFD specifications states, "Structural components shall be proportioned to satisfy the requirements of the service, fatigue, strength, and extreme event limit states at all stages during the life of the structure." Article 5.6.1 reiterates certain important assumptions for concrete behavior at the service and fatigue limit states. Article 5.9.1 specifically lists the fatigue limit state as one of the required limit states that shall be satisfied for prestressed concrete component design.

Article 5.5.3, Fatigue Limit State, defines the fatigue requirements as summarized and explained in the following:

(1) Concrete decks in multigirder bridges are exempt, as are concrete box culverts. Note that slabs in other structure types, such as concrete segmental box girders, are not covered by this exemption.
Explanation: Stresses in reinforced concrete decks and box culverts have been measured and consistently found to be low. They are far below the threshold limits and are considered to have infinite fatigue life.

(2) Where a reinforced concrete section is in compression under unfactored permanent loads and prestress, fatigue must only be considered if the tensile stress in the reinforcement under the Fatigue I load combination is greater than this permanent compression.
Explanation: Fatigue can only occur if steel is in a state of net tension. In regions where the permanent loads produce compression and live-load stresses are not sufficient to cause net tension, fatigue of steel reinforcement cannot occur. The live-load stress is taken as that produced by the Fatigue I load combination. This load combination is representative of the stress ranges, and therefore peak tensile live-load stresses, from an infrequent maximum vehicle loading. If this infrequent loading can cause net tension, fatigue must be considered, and the full stress range from the Fatigue I load combination must be used for design.

(3) Prestressed concrete components designed to meet the Service III limit state tension stress limits do not need to be checked for fatigue.
Explanation: Fatigue is checked for a single lane loaded with a modified live-load distribution factor removing the inherent 1.2 multiple presence factor in the LRFD empirical equations, impact of 15% (LRFD Table 3.6.2.1-1), and a different rear-axle spacing for the design vehicle. This results in considerably less live load than the Service III loads. The range of stress produced in the reinforcement is simply the range of concrete stress times the modular ratio and is less than the fatigue resistance of prestressing steel. This holds true only if sections are designed to be uncracked at service loads; that is, the components meet the Service III requirements. The assumption of an uncracked section does not imply that a prestressed concrete section will never crack. In fact, under certain heavy loads, it is likely that small flexural tension cracks will form but that after the passage of the load, those cracks will close. However, subsequent heavy loads that produce any tension will cause the cracks to reopen. Prevention of strand fatigue is a beneficial by-product of the LRFD requirements to design sections to be uncracked under routine service loads. This helps ensure that a section is sufficiently compressed so that only a limited number of stresses in exceedance of the tensile stress limits may occur, and that fatigue failure of high-strength strands does not occur.

(4) Whenever a concrete component is evaluated for fatigue, the Fatigue I factored stress range, $\gamma\Delta f$, must be less than or equal to the constant-amplitude fatigue threshold, $(\Delta F)_{TH}$, which is dependent on the type and configuration of reinforcement materials, and other properties:

$$\gamma(\Delta f) \leq (\Delta F)_{TN} \quad \text{LRFD Eq. (5.5.3.1-1)}$$

Explanation: As mentioned previously, concrete is checked at the Fatigue I limit state. This is a check of maximum stress range, and these stresses are compared with the constant-amplitude fatigue threshold—the range of stress at which a steel element is expected to have infinite life.

(5) For prestressed concrete bridges other than segmentally constructed bridges, the compressive stress in concrete due to the Fatigue I load combination and one-half the sum of effective prestress (after losses) and permanent loads shall not exceed $0.40 f'_c$, where f'_c is the design concrete compressive strength.
Explanation: This check limits the magnitude of cyclic compressive stress in the concrete to ensure integrity of the section under repeated compression cycles.

(6) Stresses shall be computed on a cracked section basis when the sum of unfactored permanent load stresses, stresses from effective prestress, and the tension from the Fatigue I load combination, is tensile and exceeds $0.095\sqrt{f'_c}$.
Explanation: When the computed tensile stresses on an uncracked section exceed the limit shown, the section is assumed to crack. Stresses are then computed based on an elastic cracked section. Reinforced concrete components like slab bridges or pier caps are examples in this category.

For the constant-amplitude fatigue resistance of reinforcing bars and welded-wire reinforcement, Article 5.5.3.2 includes updated resistance values that supersede those found in part 2 (Fall 2011 issue of *ASPIRE*) of Mertz's article series. These updated resistance provisions are the result of recommendations from the Transportation Research Board's second Strategic Highway Research Program Report, *Bridges for Service Life Beyond 100 Years: Service Limit State Design.*[3] The adjustment of the fatigue resistance was to achieve levels of reliability for reinforced concrete structures that are consistent with the reliability of fatigue calculations for steel structures. The resistance equation was updated for reinforcing bars and welded-wire reinforcement to achieve this consistent reliability across a family of materials. It was determined that the equations referenced in Mertz's 2011–2012 *ASPIRE* articles were overly conservative, and a more favorable resistance has been included in the AASHTO LRFD specifications since the eighth edition.

Article 5.5.3.3 provides fatigue limits for prestressing steel, Article 5.5.3.4 includes limits on welded and mechanical splices of reinforcement, Article 5.6.1 states various important assumptions that may be used for service and fatigue limit state checks, and Article 5.9.1.4 reinforces the need to check fatigue in sections where cracking is permitted under service loads.

Summary of Fatigue Design for Concrete Bridges

The following summarizes the AASHTO LRFD specifications' considerations for fatigue design:

- Prestressed concrete components designed to meet the Service III limit state requirements do not require a fatigue check.
- Concrete decks in multigirder bridges and concrete box culverts do not require a fatigue check.
- Slabs in concrete segmental box girders must be checked for fatigue.
- Reinforced concrete structures, such as slab bridges that span longitudinally, pier caps, and footings, need to be checked for fatigue. These structures commonly have low stress ranges, but there is no blanket exemption because these components are likely to be cracked in service.
- For all concrete components subjected to fatigue, the check is performed at the Fatigue I limit state and the resistance values are provided in Section 5 of the AASHTO LRFD specifications.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2010. *AASHTO LRFD Bridge Design Specifications.* 5th ed. Washington, DC: AASHTO.

2. AASHTO. 2020. *AASHTO LRFD Bridge Design Specifications.* 9th ed. Washington, DC: AASHTO.

3. Transportation Research Board. 2015. *Bridges for Service Life Beyond 100 Years: Service Limit State Design*. Strategic Highway Research Program 2 Report S2-R19B-RW-1. Washington, DC: National Academies Press. https://doi.org/10.17226/22441.

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